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Evolution of microstructure and mechanical properties during Q&P processing of medium-carbon steels with different silicon levels

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Abstract. Evolution of microstructure during heat treatment plays a fundamental role in the resulting mechanical properties of steel. Today, mechanical properties in conjunction with technological properties, such as weldability, formability, and machinability, and their optimum combinations, are widely discussed in a number of mechanical engineering disciplines. In this manner, requirements arise for developing steels which could offer high strength and good formability, and which could be used for making parts with high resistance to failure and with a long life. One present-day example of such steels involves Q&P-processed martensitic steels. Their properties are dictated by their treatment, as well as their alloying, particularly by the silicon content. Silicon fundamentally affects microstructure evolution during Q&P processing and, as a result, mechanical properties. With this way it is possible to receive microstructures consinsting of martensite and retained austenite with an ultimate tensile stress of more than 1600 MPa and a uniform elongation of more than 12 %.

1. Introduction

Under usual conditions, heat treatment of steel leads to transformation of austenite to martensite, bainite, pearlite or their mixtures, and to simultaneous precipitation of carbides. Carbides form during thermodynamic processes because the solubility of carbon in austenite and ferrite varies with temperature and with the steel's chemistry. The impact of carbide precipitates on mechanical properties is given by their morphology, size, distribution, crystal structure, and other factors. In many engineering applications, carbides are an undesirable constituent in steel, as they often impair strength properties, most notably fatigue. This adverse effect of carbide precipitation can be, to a great extent, suppressed by silicon addition. Steels with sufficient silicon levels can be unconventionally heat treated to obtain excellent strength and deformation properties [1]. One of the treatment routes that rely on the above-described principle is Q&P processing.

The Q&P process is based on carbon partitioning between martensite and retained austenite so that carbide precipitation is prevented and the excess carbon stabilizes retained austenite [2]. It involves quenching to a temperature below the M_s in order to produce a certain amount of martensite which can be controlled by choosing the quenching temperature below the M_s. This step is followed by partitioning which is beeing executed between the tempereatures of quenching and M_s. During the partitioning step carbon diffuses from martensite to austenite. As austenite becomes saturated with carbon, its stability increases. The resulting microstructure is a mixture of martensite and retained austenite and exhibits excellent mechanical properties [3-7]. However, it is imperative that

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precipitation of carbide phases is avoided during Q&P processing. If this fails, the microstructure will develop differently: the carbon atoms that diffuse from martensitic laths will not enrich retained austenite but instead create undesirable brittle carbide phases. To prevent the precipitation of carbides the silicon amount of about 1.5 - 2% should be added in steel. The silicon prevents precipitation because of its low solubility in carbides. For the formation of carbides the diffusion of silicon is necessary because they can form only in silicon depleted zones of microstructure. However the temperatures during QP processing of medium carbon steels are set to low value to be enough for diffusion of silicon and the carbides cannot form or are forming only in a limited extent [8] (figure 1).

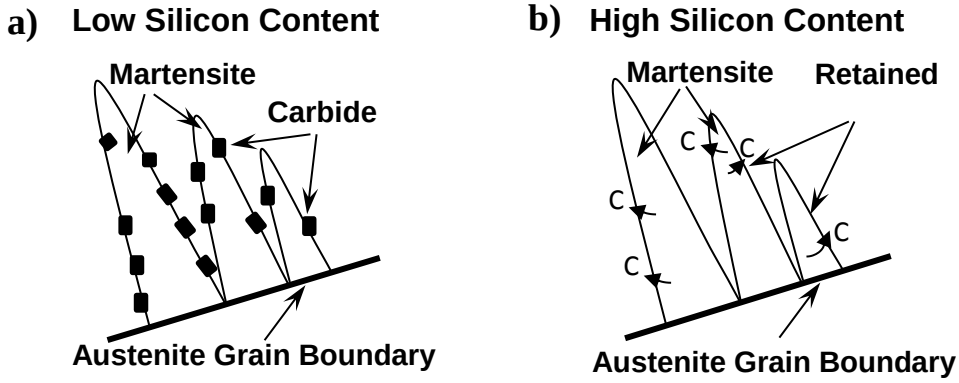


Figure 1. Effect of silicon content on the carbon partitioning mechanism during the Q&P process: a) low-silicon steel, b) high-silicon steel.

2. Experimental programme

The objective of this experiment was to compare the effects of silicon content on the evolution of microstructure and mechanical properties in two low-alloy steels with 0.43 % carbon, 0.56-0.6 % manganese, and 1.33 % chromium upon identical treatments involving the Q&P process (table 1). The only difference between them was the amount of silicon.

Table 1. Chemical composition of the experimental steels.

Steel designation	C	Si	Mn	Cr	Mo	Nb	P	S	M_s [°C]	M_f [°C]
42CrMoS4	0.42	max 0.4	0.6	1.2	0.15	-	0.03	0.04	305	184
42SiCr	0.42	2.03	0.56	1.33	0.16	0.03	0.005	0.003	298	178

To explore the effect of silicon on microstructure evolution, heat treatment routes with Q&P processing were designed (figure 2). The quenching temperatures were chosen to provide approximately 50 % martensite in the microstructure prior to partitioning. The partitioning temperatures were above and below the M_s.

The holding time at the partitioning temperature was 600 s. The specimens had a diameter of 8 mm. Prior to the experimental heat treatment, they were annealed at 1050 °C for 20 minutes. The experiment was carried out in a thermomechanical simulator that used induction-resistance heating.

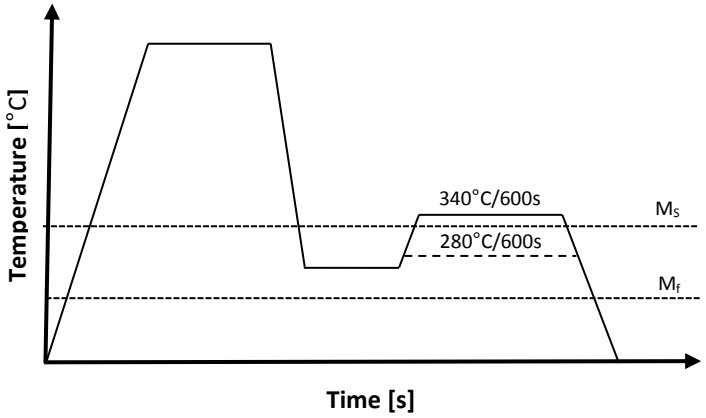


Figure 2. Diagram of the heat treatment route with the Q&P process.

3. Results and discussion

3.1 Microstructure analysis

Microstructures of the specimens were examined using scanning electron microscopy. Therefore samples were etched with 4 % picral (for 30 seconds), and 10 % Na2S2O5 solution (for 180 seconds) after grinding and polishing. Phase composition was examined using TESCAN Vega microscope image analysis For better resolution capability, the micrographs were processed by image transformation.

Using SEM, mixed microstructures of tempered and untempered martensite and bainite were found in the specimens (figures 3 and 4). The microstructure of the 42CrMoS4-QP280 specimen was a mixture of tempered and untempered martensite with lath morphology (figure 3-a). Close examination of the microstructure revealed the presence of fine carbides. The 42CrMoS4-QP340 specimen contained a mixture of tempered lath martensite and lower bainite which were, however, impossible to distinguish with certainty due to their similar appearance (figure 3-b). With regard to the differences in the microstructures of the specimens of the 42CrMoS4 steel, it can be said that austenite stabilization has not occurred in the 42CrMoS4-QP340 specimen. Therefore, the austenite decomposed and due to low silicon content, a bainite-like microstructure formed.

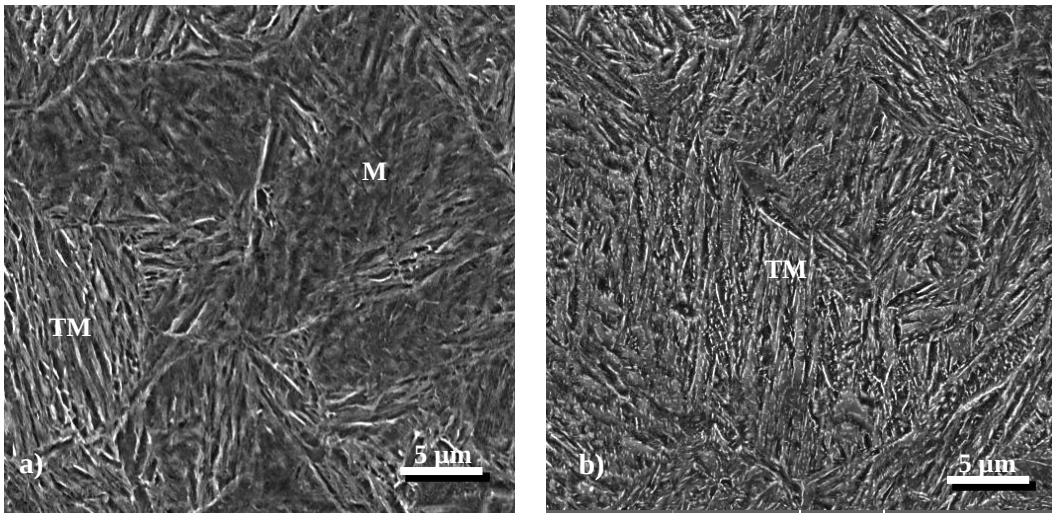


Figure 3. SEM-Micrographs of 42CrMoS4 specimens after Q&P processing obtained using SE mode (phase contrast). a) QP-280 – Mixture of lath tempered martensite (TM) and untempered martensite (M), b) QP-340 – Mixture of lath tempered martensite (TM) (and bainite).

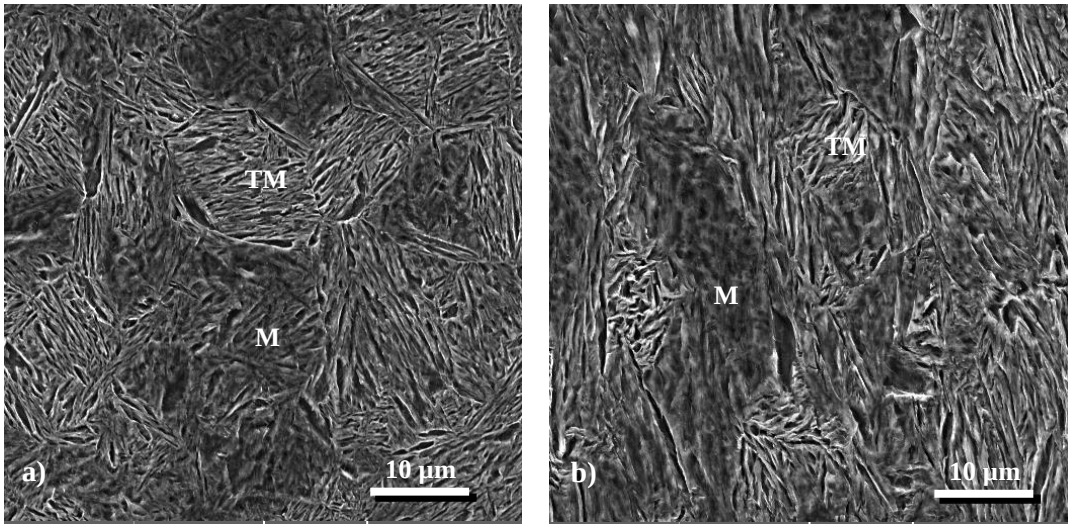


Figure 4. SEM-Micrographs of 42SiCr specimens after Q&P processing obtained using SE mode (phase contrast). Mixture of lath tempered martensite (TM) and untempered martensite (M) in a) QP-280 and b) QP-340.

Both specimens 42SiCr-QP280 and 42SiCr-QP340 contained low-temperature tempered and untempered lath martensite (figure 4). This shows that in this steel, unlike in 42CrMoS4, partitioning at 340 °C has not led to austenite decomposition into bainite. Here, austenite remained present up until the last phase of the treatment. Therefore, it transformed to martensite during quenching (figure 4-b). Both observed martensites had lath morphology. The laths were free from visible carbide precipitates. This confirms the assumption that in order for austenite to stabilize during the Q&P process the steel must contain a sufficient amount of silicon, which prevents carbides from forming.

3.2 Mechanical properties

Mechanical properties were determined by means of standard-based static tensile testing of miniature test pieces [1]. The ultimate strength (UTS) and yield stress (YS) values were comparable in both 42SiCr-QP-340 and 42CrMoS4-QP-340 (table 2). The QP-280 route led to the highest ultimate strength of 1891 MPa in the 42SiCr steel, although the yield stress was lower than that of the 42CrMoS4 steel by approximately 240 MPa (figure 5).

A significant difference between the investigated steels was the value of uniform elongation, which in the case of steel 42SiCr reached values of 9-12% in the case of steel 42CrMoS4 of 4-6%.

Table 2. Mechanical properties of the experimental steels.

Specimen designation	YS [MPa]	UTS [MPa]	A [%]
42CrMoS4-QP-280	1308	1786	4
42CrMoS4-QP-340	1398	1649	6
42SiCr-QP-280	1067	1891	9
42SiCr-QP-340	1394	1665	12

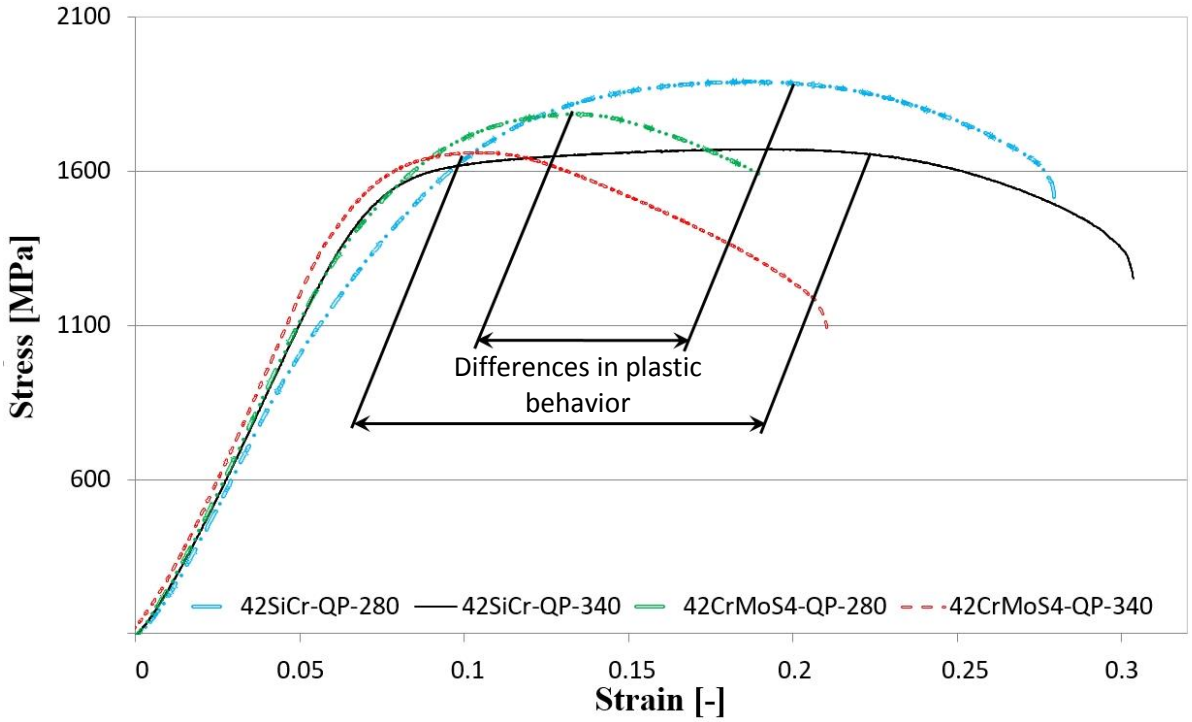


Figure 5. Stress-strain plots for specimens of the 42SiCr and 42CrMoS4 steels upon Q&P processing.

The results of evaluation of microstructure showed the presence of tempered and untempered martensite (and bainite) in the structure of the experimental steels. In the case of steel 42CrMoS4 fine carbides were observed in the martensite, which originated during the step of quenching.

The carbide precipitation also occurred during the decomposition of austenite to bainite structure type. In contrast, in steel 42SiCr most likely occurred due to the higher content of silicon to stabilization the retained austenite as thin films between martensite laths. The presence of austenitic films could be the reason for higher uniform elongation for 42SiCr steel samples. This conclusion, however, will be subject to further research with respect to the detailed description of the structure using TEM and other analytical methods.

Regarding to ultimate tensile strength it can be stated, that in case of steel 42CrMoS4 lower values compared to steel 42SiCr were achieved. This may be caused by carbide precipitation, or a different volume ratio of tempered and untempered martensite or austenite grain size etc. Identifying the true cause will be next step of future research.

4. Summary and conclusion

An experiment that compared two steels, whose alloying only differed in the silicon content, was carried out to explore the hypothesis that in order for Q&P processing to be successful, carbide formation must be prevented. The presence of silicon during Q&P processing enables carbon to diffuse from martensite into austenite, to enrich and therefore stabilize it. As a result, martensitic-austenitic microstructures can form which exhibit high strength and good ductility.

The effects of parameters of the Q&P process on the evolution of microstructure and mechanical properties were examined in two low-alloy steels that contained 0.42 % carbon and very similar levels of manganese and chromium. There were different silicon levels. In 42CrMoS4, the silicon content was 0.4 %, whereas in 42SiCr, it was 2 %.

The Q&P process route was designed to produce approximately 50 % martensite at the end of quenching. The subsequent partitioning steps involved temperatures below and above the M_s.

In those specimens of the 42CrMoS4 and 42SiCr steels that underwent partitioning below the M_s, the resulting microstructures contained a mixture of tempered and untempered lath martensite. Fine carbide precipitates were found in the 42CrMoS4 steel with a low silicon content. The specimens of 42SiCr showed a strength of 1891 MPa and uniform elongation of 9 %. The average ultimate strength and uniform elongation of the specimens of the 42CrMoS4 steel were 1786 MPa and 4 %, respectively.

The Q&P process routes which involved partitioning above the M_s led to different microstructure evolution. In the 42CrMoS4 steel, a mixed microstructure of tempered martensite and, most likely, lower bainite formed. The latter was a product of decomposition of the untransformed austenite during partitioning. By contrast, the microstructure of 42SiCr – which had a high silicon level – consisted of tempered and untempered martensite without any carbide precipitates. Ultimate strengths in both experimental steels were comparable. The average uniform elongation of the 42SiCr steel was 12 %, whereas in 42CrMoS4, it was 6 %.

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